Voice Features as the Diagnostic Marker of Autism

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***Abstract*—**The aim of the study is to determine the acoustic features of voice and speech of children with autism spectrum disorders (ASD) as a possible additional diagnostic criterion. The participants in the study were 95 children with ASD aged 5-16 years, 150 typically development (TD) children, and 103 adults – listening to children's speech samples. Three types of experimental methods for speech analysis were performed: spectrographic, perceptual by listeners, and automatic recognition. In the speech of children with ASD, the pitch values, pitch range, values of frequency and intensity of the third formant (emotional) leading to the "atypical" spectrogram of vowels are higher than corresponding parameters in the speech of TD children. High values of vowel articulation index (VAI) are specific for ASD children's speech signals. These acoustic features can be considered as diagnostic marker of autism. The ability of humans and automatic recognition of the psychoneurological state of children via their speech is determined.

***Keywords*—**Autism spectrum disorders, biomarker of autism, child speech, voice features.

I. Introduction

THE research on human state reflection in voice and speech parameters begins with works of Charles Darwin [1]. On this topic, there are the number of studies on characteristics of cries of babies with different diseases [2]-[6] and creating automatic classification systems for recognizing a child's state by crying [7]-[9]. The features of speech in humans in different physiological states [10], with various neuropsychiatric status [11], and changes in the speech features depending on the speaker's emotional state [12], [13] are studied. It was established that paralinguistic characteristics are leading in the recognition of the speaker's state: tempo, rhythm, intonation, pitch.

Now the studies conducted by different research groups are aimed at finding speech markers of diseases diagnostics of which is difficult due to a variety of symptoms. One of these developmental disorders is autism spectrum disorders (ASD, F 84.0 according ICD-10). The search of autism biomarkers is based on the main symptoms of ASD: social disorders connected with the interaction between mother and infant [14] and adult speech addressed to the child [15], the motor sphere [16] and the acoustic features of speech [17].

Multiple symptoms of disorders joined in the "autistic triad" including the violation of social behavior and speech, limited forms of behavior and a tendency to stereotypes [18], [19], the degree of its intensity, the age of manifestation of all specific symptoms, the presence of a leading complex of symptoms are individual for children with ASD. A variety of symptoms is associated with abnormal development and functioning of the central nervous system (CNS) [20]. CNS damage may occur in the early stages of pregnancy, starting with the fifth week of prenatal life [21], or in the early postnatal period [20].

All researchers agree on specific speech disorders in individuals with ASD, the differences only concern certain speech features e.g. [17], [22], [23]. Neuroanatomical studies of speech areas of the cerebral cortex showed a decrease in the density of neurons in Wernicke's area (Broadman area 22) and angular gyrus (area 39), an increase in the density of glial cells in these areas and in Broca's area (area 44) in patients with ASD vs. typically developing peers [24]. Structural changes in speech areas of the cerebral cortex, disorders and weakening of the integrative brain function [25], [26] may be crucial for the occurrence of speech and communication disorders. Symptoms of ASD are most expressed in childhood, symptoms in adults are more diverse, but less clear because of somatic [27] and mental defects [28].

A wide range of speech disorders is described for children with ASD: from the rough delay of formation to the outstripping development rate. The prevailing number of works focuses on the analysis of speech of children with high functional autism (HFA) [29]. The features of intonation, timbre, voice modulation are described; violations of the speech pragmatics are revealed [30], [31]. Phonological disorders have been shown to be expressed more than lexical disorders, with a general level of speech formation being low [32].

From the first descriptions of symptoms of autistic disorders [18], abnormal prosody of speech of patients was identified as the main feature [33] that was further confirmed by many researchers [17], [34]-[37]. Most patients have difficulty controlling their pitch. Their speech is characterized by atypical word and phrasal stress [38]-[41]. Prosody plays a leading role in the process of verbal communication and establishment of social contacts between people. The specific prosody caused by the phrasal stress and the stressed syllable accentuation in a word is a characteristic feature of children with ASD [42] which impedes verbal communication. However, the verbal response is not replaced by a gesture as the difficulties in using gestures in children with ASD are noted [43]. It should be noted that the pragmatic level of speech organization in persons with HFA is violated. The works of Paul et al. [35] found prosodic disorders only in 47% of 30 adults with HFA. They compared the HFA and participants of the control group in performing different tasks connected with the perception and pronunciation of specific

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prosodic elements. The results revealed differences in the prosodic stress perception and production between groups. Authors suggested that understanding and developing appropriate accent patterns are difficult for participants with HFA [35].

The methods of instrumental analysis of voice and speech parameters are widely used in the study of speech features of informants with ASD. However, the data on acoustic characteristics of speech of ASD children are contradictory. In Kanner's pioneering work [18], the speech of patients with ASD is described as monotonous, mechanical, with a flat intonation. The monotony of speech is also described in another study which shows that pitch variation (by estimating the coefficient of pitch variability in each word of the utterance) in Japanese 4-9 year old children with ASD is less than in healthy children [23]. Similar data on the absence of significant differences in pitch and pitch range in 7-17 year old HFA children [38] and children with Asperger's syndrome [44] vs. TD peers are revealed.

Opposite results were obtained by other researchers. They show that the speech of children with ASD is characterized by high pitch values and its variability. The data were obtained in the study of the speech of 8-9-year-old Portuguese children [45], 4-10 year old bilinguals (Hindi – English) [46], English school students with HFA [39], 4-6.5 year old Israeli children [17], 4-14 year old Russian children and adolescents [47], [48].

The pitch is established to be a specific feature of children with autism aged 5-14 years and children for whom ASD accompanies the main neuropsychiatric disease, but the pitch values in children with autism are significantly higher than in children with ASD as accompanying symptoms [47], [48]. An increased pitch range may indicate a delay in speech development in children with ASD [46].

The atypical spectrum of speech signals along with high pitch values and its variability is indicated [17]. The specificity of the spectrum (by averaging the spectrum of one - minute speech) of speech of children with ASD vs. the corresponding feature of TD children's speech is revealed. This finding supposes the possibility of using spectral features as quantitative objective biomarkers of ASD children's speech [17]. The data on the atypical spectrogram of the speech signal are supplemented by experimental results about expressed high-frequency components of the spectrum for account of high values of the third (emotional) formant and its amplitude normalized with respect to the pitch amplitude [48]. Thus, the similar data on acoustic characteristics of the voice and spectral features of the speech of ASD informants were obtained on the material of different languages, but for Russian language those data are single.

The aim of our study is to determine the acoustic features of voice and speech of children with ASD as a possible additional diagnostic criterion.

II. Methods

A. Data Collection

Speech material of children with ASD was taken from the speech database "AD-Child.Ru" [49]. The participants in the study were children with ASD (F84.0 according to ICD-10), biologically aged 5-16 years (n = 95 children), typically developing (TD) children (coevals, n =150) and 103 adults – listeners. The sample of children with ASD was divided into two groups: the first group consisted of children with reverse development at the age of 1.5-3.0 years (ASD-1), the second group consisted of children with a risk of development identified at birth (ASD-2), and autistic symptoms are caused by neurological diseases. Total scores on the Childhood Autism Rating Scale (CARS) [50] were used to assess the severity of autistic disorders and calculated for each group. CARS were filled out by the parents of the children, and the conclusions were made by the child psychiatrist. We used a standard protocol for recording children's speech, including the most similar situations: a dialogue with the experimenter with a standard set of questions, a situation with viewing pictures and telling a story about them (with and without the experimenter's prompt), taking into account the abilities and age of the children. The speech recording was made on certified equipment: a "Marantz PMD 660" recorder with an external microphone "SENNHEIZER e835S" in laboratory conditions. The speech file format was Windows PCM, 44,100 Hz, 16 bits per sample.

B. Data Analysis

Three types of experimental methods for speech analyzing were performed: spectrographic, perceptual by listeners and automatic recognition.

The sound editor Cool Edit Pro 2.1 was used for spectrographic analysis of speech. Pitch values (F0), pitch range [F0max-F0min], formants frequency (F1-first formant, F2-second formant, F3-third formant), energy (E) and duration of vowels in speech samples were determined. The choice of these characteristics is due to the physiological processes in the vocal tract - the frequency of the vocal folds vibration and articulation processes in the oral cavity. The values of the VAI [51] were calculated to determine the clarity of pronunciation of speech sounds.

The goal of the perceptual study was to reveal the possibility of listeners to recognize the child's state – developmental disorders or typical development via speech.

Study 1: The test sequences included words from spontaneous speech of 5-7 years old children (n = 2 tests, for 30 samples of in ASD test, and for 30 samples of in TD test). In the test, each speech sample was presented once. The interval between speech samples was 5 s. The test sequences were presented to listeners –1-year pediatric students (n = 26, age – 18.1 ± 1.2 y (Average ± Std)) and information technology (IT) master students (n = 13, age 24.4 ± 3.8y) for perceptual analysis. The listeners had noted the severity of the developmental disability (TD – disorders: mild or severe).

Study 2: Two test sequences were created which contained speech material (60 speech samples) of children aged 6-11 years (ASD-1 – 4 children; ASD-2 – 6 children). The participants of the study were students – 1-year pediatric students – Russian-native speakers (n = 43, age – 18.4 ± 0.6 years) and speakers of foreign languages (n = 21, 21 ± 1.9 years). The task of the perceptual study was to recognize the psychoneurological state of children (developmental disorder – typical development) while listening to their speech. The number of correct answers of the listeners was counted.

Gaussian Mixture Models (GMM) for automatic classification of the psychoneurological state of 7-10 years old children by the characteristics of their voice were used. The relative measures of classification quality were used as indicators of the effectiveness of automatic recognition of states: The accuracy of a system within a class (precision) is the proportion of samples that actually belong to a given class, relative to all samples that the system has assigned to this class. Recall is the proportion of samples that belong to a class found by the classifier relative to all samples of this class in the test sample. Accuracy - the proportion of samples for which the classifier made the right decision.

Statistical analysis: Statistical analysis was performed using "STATISTICA 10". Non-parametric criteria – Mann -Whitney test, regression analysis and Spearman correlation were used.

Ethical approval was obtained from the Ethics Committees (Health and Human Services, HHS, IRB 00003875, St. Petersburg State University), and written informed consent was obtained from parents of the child participant.

III. Results

A. *Acoustic Features of Speech*

In children with ASD in all age the pitch values are significantly higher ($p < 0.001$ - Mann-Whitney test) than the corresponding features of TD children, in ASD-1 children they are significantly higher ($p < 0.001$) vs ASD-2 children that was shown in the analysis of spontaneous speech (Fig. 1).

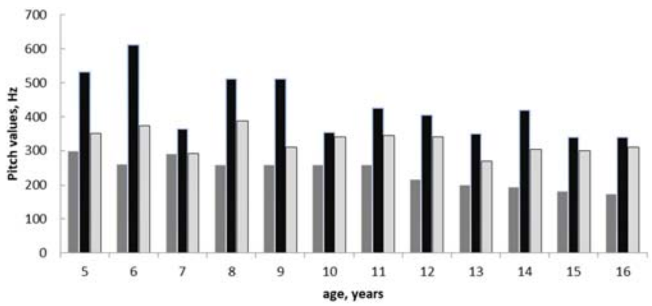

Fig. 1. The acoustic features of children's speech – pitch values of vowels. Vertical axis – pitch values, Hz, horizontal axis – child age, years. Dark grey color – data for TD children, black color – for ASD-1 children, light gray color – for ASD-2 children

The duration of vowels in speech samples of children with ASD -1 and ASD -2 does not differ significantly. Significant differences in the acoustic features of speech in children with ASD and TD children were revealed (Table I).

TABLE I
DIFFERENCES IN THE ACOUSTIC FEATURES OF SPEECH IN CHILDREN WITH ASD AND TD AND WITH ASD-1 AND ASD-2 CHILDREN (MANN -WHITNEY TEST)

Acoustic features	TD vs ASD-1	TD vs ASD-2	ASD-1 vs ASD-2
F0	< 0.001	< 0.001	< 0.05
F0max-Fmin	< 0.001	< 0.01	< 0.05
F3	< 0.001	< 0.01	< 0.01
E3/E0	< 0.001		< 0.01
VAI		< 0.05	< 0.01

The range of three formant frequencies (F1, F2, F3) for ASD-1 and ASD-2 children with the characteristics of the F-pattern of vowels, which are determined by the phonemic affiliation and phonetic quality of the vowel individual, the characteristics of the speaker and the anatomical dimensions of the vowel tract, are analyzed (Table II).

TABLE II
THREE FORMANT FREQUENCIES (F1, F2, F3) RANGE OF STRESSED VOWELS FROM SPEECH SAMPLES OF CHILDREN WITH ASD-1 AND ASD-2

F, Hz	ASD-1	ASD-2
F1	300-1376	377-1218
F2	560-5087	372-3833
F3	1027-7657	1044-5876

The maximum frequency range of the first and second formant for ASD-1 children is shown. These data and the VAI values indicate that ASD-1 children articulate vowels in words more clearly than ASD-2 children.

The correlation between the severity of autistic disorders (based on the conclusion of a child psychiatrist and scores on the CARS scale) and the ASD child's speech formation was determined. For children aged 5-11 years, the correlation between CARS scores and the level of speech formation was determined: vocalization, syllables, simple words, and simple phrases $F(1,35) = 10.634$ $p < 0.0001$ ($\beta = -0.483$ $R^2 = 0.233$) - Regression analysis, the higher the scores, the lower the level of speech development. For ASD children 13-15 years old, a correlation $F(1,159) = 53.679$ $p < 0.0001$ ($R^2 = 0.161$ $\beta = -0.402$) between the pitch values for the phrases and CARS verbal scores is shown.

B. *Perceptual Data: Listeners Recognition of the State of TD Children and Children with ASD Aged 5-11 Years*

Study 1: Both groups of auditors attributed more speech signals of 5-7 year-old children with typical development to the TD category (60% correct of answers of pediatrician students, 78% responses from IT - student). Pediatric students attributed more speech signals of children with ASD to the category of mild developmental disorders (42% of answers) vs IT-student (35%) and to the category of severe developmental disorders - 35% answers vs 22% answers.

Study 2: Listeners, regardless of their experience in interacting with children and language classified more than 50% of children with ASD as TD children aged 6-11 years (Russians – 62.9% and 53.3% of answers, respectively, listeners with and without experience in interacting with children; foreigners – 59% and 61.1% of answers, respectively). Developmental disorder in a larger number of answers (47.7%) was noted by the group of Russian listeners with experience in interacting with children (Table III).

TABLE III
RECOGNITION THE PSYCHONEUROLOGICAL STATE OF ASD CHILDREN BY LISTENERS - DEVELOPMENTAL DISORDER - TYPICAL DEVELOPMENT”

Group of listeners	Developmental disorder	TD
Russians-without experience	37.1	62.9
Russians-with experience	47.7	53.3
Foreigners-without experience	41	59.0
Foreigners-with experience	38.9	61.1

The statistical analysis (Spearman, $p < 0.05$) showed a correlation between the determination by foreign listeners of the child’s state (typical development) and the child’s developmental disorders ($r = 0.75$); between recognition by Russian and foreign listeners of developmental disorder (0.67).

C. Automatic (Machine) Recognition of the State of TD Children and Children with ASD Aged 7-10 Years

The possibility of automatic recognition of the psychoneurological state of children is shown (Table IV). The state of TD children is automatically determined better by their speech samples as belonging to children with typical development. The state of ASD children is determined with less accuracy (speech samples belong to children with atypical development).

TABLE IV
ACCURACY OF AUTOMATIC RECOGNITION OF CHILDREN’S PSYCHONEUROLOGICAL STATE: PRECISION AND RECALL

Group of children	Precision	Recall
TD	0.848	0.706
ASD	0.602	0.676

IV. CONCLUSION

We found significant differences in pitch values, pitch range, VAI, formants frequency and energy between ASD groups and between ASD and TD children in spontaneous speech. We propose to use acoustic features of the voice and speech as a diagnostic criterion for ASD: high pitch values, pitch range, well-marked high-frequency in spectrum, intensity of the third formant, high values of the VAI. These acoustic features, which are simultaneously present in the speech of children with ASD, may be biomarker of autism.

The choice of speech as a biomarker of autism is due to the functions performed by speech, which allows us to consider speech as a system-forming factor of behavior. The use of noninvasive methods for assessing speech at different levels of its organization makes it possible to study informants with ASD accompanied by behavioral disorders.

Adults are able to determine the child’s state (typically development – developmental disorders) by the speech samples.

In our study, on the material of the Russian language, an automatic classification of the state of children (typical development - developmental disorder) was carried out according to their speech.

V. DISCUSSION

The acoustic features of speech of children with ASD, which can be used as a diagnostic criterion and could be considered as a biomarker of autism, are described on the material of Russian language.

The results of this study, on the one hand, confirm the data obtained from different languages, which mainly concern the voice characteristics in ASD informants [17], [40], [46]. On the other hand, the results indicate an additional feature caused with articulatory processes occurring in the oral cavity – the VAI in children’s speech. As far as we know, other researchers have not considered VAI when identifying specific speech features of children with ASD. VAI values are most important for comparing the speech specificity of ASD children with speech peculiarities in other disorders, such as intellectual disabilities (ID) [52].

The present study, conducted on a larger sample of children with ASD, is a continuation of the studies of the acoustic features of the speech of ASD children. It was shown on the sample of 25 ASD children aged 5-14 years that the ASD children differ from TD children on the base of higher values of pitch, pitch values variability, and formant characteristics. These acoustic features and well-marked high-frequency in spectrum were more clearly presented in the speech of the first group ASD children than the second group ASD children [47]. Pitch values of stress vowels were significantly higher: in spontaneous speech vs. repetition words of the first and second group ASD children, and TD children aged 7-12 years; in the spontaneous speech of the first group ASD children than in the second group [48]. The ability of listeners to determine the gender, age and psychoneurological state of children was shown in a perceptual experiment when listening to speech samples of 4-11 year old children with ASD [53]. In two perceptual experiments in our study, the possibility of correct recognition of the state of 5-11 years old ASD children by adults is also shown.

In the future, the acoustic features of the speech of ASD children will be compared with the speech features of children with ID. One of approaches to the study of speech of children with ASD is comparing with the development of speech in children with ID. According to WHO, 50% of children with ASD have intellectual disabilities. ID (F70-F79) is a state of delayed or incomplete intellectual development characterized by a decrease in skills that arise in the development process and skills that determine the general intelligence level, i.e. cognitive abilities, language, motor skills, social activity. According to various data, children with ID make up about 1% of the population of 3-10 year old children [54]-[56]. ID can occur against the background of another mental or physical disorder or without it. Children with intellectual disabilities are characterized by a delay in speech development at different levels: syntax, vocabulary, speech intelligibility [52], [57]-[59]. In children with ASD, the speech intelligibility is associated with the non-formation of consonant phonemes, with a clear articulation of vowels in words being possible

[48]. From one point of view, the speech development of children with ID is similar to TD children trend. Authors revealed that understanding speech utterances in children with ID is analogous to the perception of TD children of younger age [60]. From the other point of view, children with ID have their own way of speech development as children with ID require more extensive vocabulary for constructing and understanding sentences than TD children [61]. The similarity of speech disorders of children with ID and ASD is described. Repetitions and stamps are specific features of children with ID and ASD, but they persist in children with ASD at an older age than in children with ID. Children with ID use dialogue speech, but do not practically use monologues; speaking children with ASD have a monologue speech developed better than in children with ID. These data suggest that certain similarities in speech disorders of children with ID and ASD do not allow using the verbal component of speech as a distinctive feature of diseases.

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